# THEORETICAL RATIOS FOR THE EUV LINES OF Al VIII IONS

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**Abstract.** Theoretical line ratios for the Al VIII ion have been investigated using an atomic model including the first fifteen energy levels, and taking account of various physical processes. The line emissivities as a function of electron density have been computed. Density-dependent theoretical line ratios are presented and their diagnostic applications in the solar atmosphere are discussed with the help of theoretical line intensities computed using an atmospheric model for the quiet Sun.

## 1. Introduction

Diagnostics of highly stripped solar ions have been the subject of extensive studies since the advent of space research and there exists a vast literature on the topic including the recent review by Dwivedi (1994a). EUV emission lines from carbon-like ions have been observed in the spectra of astrophysical objects such as planetary nebulae (Pottasch *et al.*, 1985) and the solar atmosphere (Vernazza and Reeves, 1978). Density and temperature measurements from these ions have been extensively studied (Mason and Bhatia, 1978; Raju and Dwivedi, 1979; Keenan *et al.*, 1986; Dwivedi and Gupta, 1993). Al VIII, which is a less-abundant ion of the carbon sequence, has not previously been studied. Recently, Dwivedi (1994b) discussed the possibility of using the Al VIII $\lambda285.46/\lambda323.52$ line ratio for density diagnostics, since these lines are within the range of the SERTS observations by Thomas and Neupert (1994). According to the ionisation equilibrium calculations of Arnaud and Rothenflug (1985), the Al VIII ion has its maximum ionic concentration at $8.1 \times 10^5$ K. Dwivedi and Gupta (1991) and Keenan *et al.* (1994) have shown the importance of emission lines from the less abundant Al IX ion (boron sequence) for density diagnostics. Recently, Raju, Dwivedi, and Gupta (1994) studied the theoretical pressure structure in the transition region from lines of the Na VII and Al IX ions. We have, therefore, taken up the Al VIII ion for diagnostic studies of the solar plasma. Since only scanty observations exist for this ion in the EUV spectra presently available, we have calculated the absolute line intensities for this ion using a spherically-symmetric model atmosphere of the quiet Sun by Elzner (1976).

In the following section, line emissivities and the atomic data used are discussed. We present results and discussion in Section 3. The last section concludes this paper.

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## 2. Line Emissivity and Atomic Data

The line emissivity per unit volume, per unit time, for an optically thin spectral line is given by

$$\epsilon(\lambda_{ij}) = \frac{1}{4\pi} N_j A_{ji} \frac{hc}{\lambda_{ij}} \text{ergs cm}^{-3}\ \text{s}^{-1}\ \text{sr}^{-1}\ , \tag{1}$$

where $A_{ji}$ is the spontaneous transition probability and $N_j$ is the number density of the upper level $j$ which can be parameterised as

$$N_j(X^{+p}) = \frac{N_j(X^{+p})}{N(X^{+p})} \frac{N(X^{+p})}{N(X)} \frac{N(X)}{N(H)} \frac{N(H)}{N_e} N_e\ .$$

Here, $X^{+p}$ is the $p$th ionisation stage of the element $X$; $N(X^{+p})/N(X)$ is the ionisation ratio of the ion $X^{+p}$ relative to the total number density of the element; $N(X)/N(H)$ is the abundance of the element $X$ relative to the hydrogen, which may or may not be constant in the solar atmosphere; $N(H)/N_e$ is the hydrogen abundance which is usually assumed to be 0.8 for a fully ionised plasma, and finally $N_j(X^{+p})/N(X^{+p})$ is the population of level $j$ relative to the total number density of the ion $X^{+p}$ and is determined by solving the statistical equilibrium equations for the ion.

Thus the emissivity can be written as

$$\epsilon(\lambda_{ij}) = \frac{1.59 \times 10^{-8}}{4\pi\lambda_{ij}\ (\text{Å})} A_{ji} \frac{N_j(X^{+p})}{N(X^{+p})} \frac{N(X^{+p})}{N(X)} \frac{N(X)}{N(H)} N_e\ . \tag{2}$$

The line intensity can therefore be expressed as

$$I(\lambda_{ij}) = 1.265 \times 10^{-9} \int \epsilon^*(\lambda_{ij}) N_e\, \mathrm{d}h\ (\text{cm})\ \text{ergs cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ , \tag{3}$$

where

$$\epsilon^*(\lambda_{ij}) = \frac{A_{ji}}{\lambda_{ij}\ (\text{Å})} \frac{N_j(X^{+p})}{N(X^{+p})} \frac{N(X^{+p})}{N(X)} \frac{N(X)}{N(H)}\ .$$

The intensity ratio of two lines emitted from the same ion can, therefore, be expressed as

$$\frac{I(\lambda_{ij})}{I(\lambda_{kl})} = \frac{A_{ji}}{A_{lk}} \frac{\lambda_{kl}}{\lambda_{ij}} \frac{N_j(X^{+p})}{N_l X^{+p})}\ . \tag{4}$$

The schematic energy level atomic model comprising the first 15 levels of the Al VIII ion is shown in Figure 1. The ground configuration consists of a $^3P$, a $^1D$, and $^1S$; and the higher configuration forms a $^5S$, a $^3D$, a $^3P$, a $^1D$, a

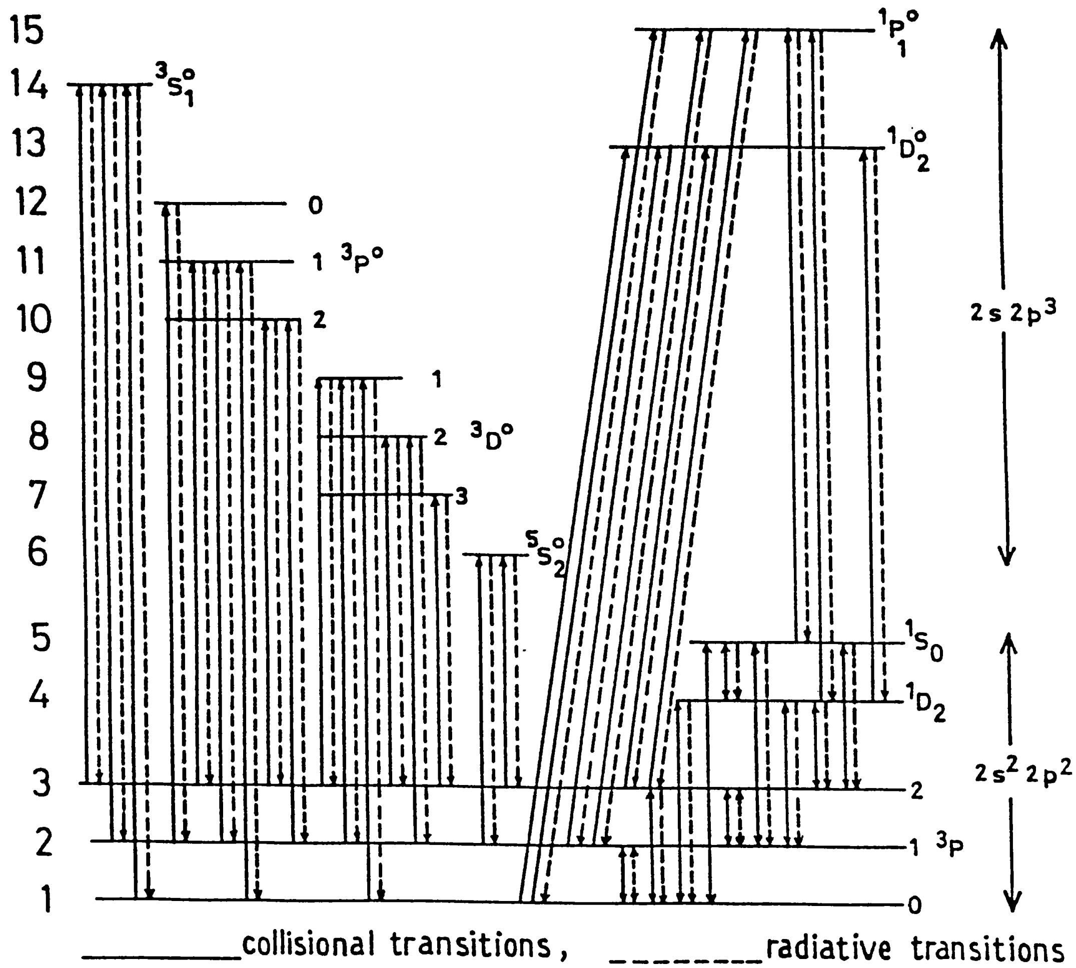


Fig. 1. Schematic energy level atomic model for Al VIII ion.

$^3S$, and a $^1P$ term. The collisional processes are shown by solid lines and the radiative processes by broken lines. The atomic data needed to compute the line intensities are the following: (i) wavelengths, (ii) radiative transition probabilities, and (iii) collision strengths. The transition probabilities and the wavelengths for the forbidden transitions of the Al VIII ion have been taken from Nussbaumer and Rusca (1979). The wavelengths for the allowed transitions have been taken from the tabulation of Kelly and Palumbo (1973). The transition probabilities for allowed transitions are obtained by interpolation along the ions of the carbon sequence, using values from Mason and Bhatia (1978) for Mg VII, Si IX, and S XI ions. The collision strengths have been obtained by interpolation along the ions of carbon sequence in the following manner.

For the reasons discussed by Dwivedi and Gupta (1993), in the case of forbidden transitions, the collision strengths for Ne V, Mg VII, and Si IX from Aggarwal (cf. Aggarwal, 1986, and references cited therein) were used for interpolation. For allowed transitions, we have used the Mason and Bhatia (1978) values for Mg VII, Si IX, and S XI for interpolation.

TABLE I

Theoretical line intensities using a model atmosphere of Elzner (1976)

$N(\mathrm{Al})/N(H) = 2.7 \times 10^{-6}$ (Meyer, 1985)

| Transition ($2s2p^3 - 2s^2 2p^2$) | | Wavelength (Å) | Intensity (ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$) computed | observed |
|---|---|---|---|---|
| $^3S_1^0 - ^3P_0$ | (14,1) | 247.40 | 0.275 | |
| $^3S_1^0 - ^3P_1$ | (14,2) | 248.46 | 0.824 | |
| $^3S_1^0 - ^3P_2$ | (14,3) | 250.14 | 1.390 | |
| $^1P_1^0 - ^1D_2$ | (15,4) | 251.35 | 0.079 | |
| $^1D_2^0 - ^1D_2$ | (13,4) | 285.47 | 0.186 | 27.3[a] |
| $^1P_1^0 - ^1S_0$ | (15,5) | 287.08 | 0.018 | |
| $^3P_1^0 - ^3P_0$ | (11,1) | 323.52 | 0.355 | |
| $^3P_2^0 - ^3P_1$ | (10,2) | 325.31 | 0.389 | |
| $^3P_2^0 - ^3P_2$ | (10,3) | 328.20 | 1.420 | |
| $^3D_0^0 - ^3P_1$ | (9,1) | 381.15 | 0.421 | |
| $^3D_1^0 - ^3P_1$ | (9,2) | 383.70 | 0.255 | |
| $^3D_2^0 - ^3P_1$ | (8,2) | 383.78 | 0.928 | |
| $^3D_3^0 - ^3P_2$ | (7,3) | 387.97 | 1.535 | |

[a] SERTS observation for active region (Thomas and Neupert, 1994).

We have also taken account of proton excitation for the $^3P_0 - ^3P_2$ and $^3P_1 - ^3P_2$ transition and photo-excitations for the $^3P_0 - ^3P_1$ and $^3P_1 - ^3P_2$ transitions. In interpolating the proton excitation rates, we have used the respective values for the Mg VII and Si IX ions given by Mason and Bhatia (1978). The photo-excitation rate is calculated from the expression (DeBoer *et al.*, 1972)

$$R_{ij} = \frac{g_j}{g_i} A_{ji} (e^{h\nu_{ij}/kT_r} - 1)^{-1} d ,$$

where $g_j$ and $g_i$ are the statistical weights of the levels $j$ and $i$, respectively. $A_{ji}$ is the spontaneous transition probability, $d$ is the dilution factor and is assumed to be 0.5 for the sake of simplicity. $T_r$ is the radiation temperature and is obtained from the solar black body emission formula, using the continuum flux at a given wavelength (Allen, 1973):

$$J_\nu = \frac{2h\nu^3}{c^2} (e^{h\nu/kT_r} - 1)^{-1} .$$

## 3. Results and Discussion

The computed Al VIII line intensities for a spherically-symmetric model of quiet Sun is given in Table I. Thomas and Neupert (1994) have identified the Al VIII

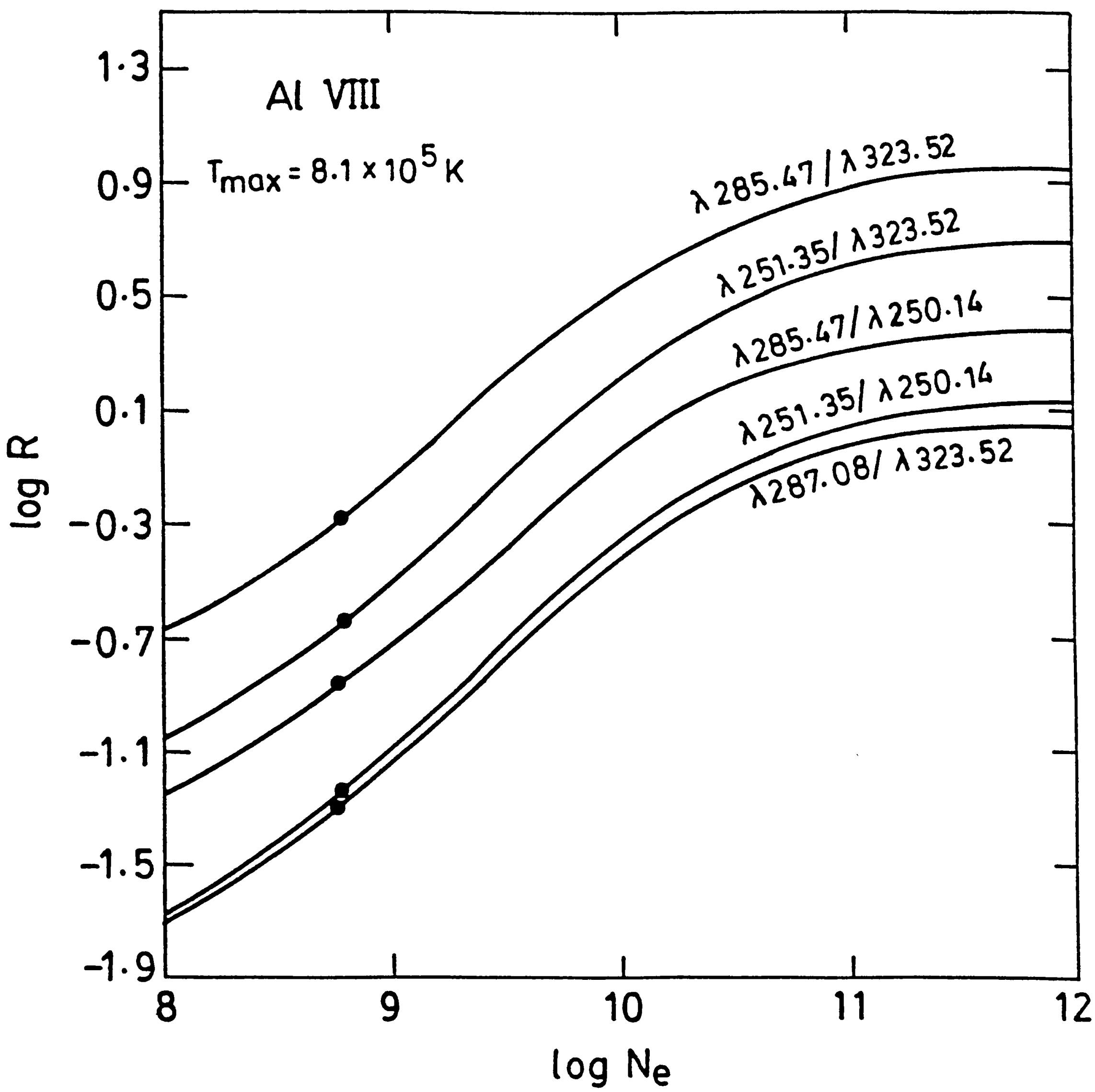


Fig. 2. Theoretical line ratios as a function of electron density. Dots correspond to the theoretical line intensity ratios for a model atmosphere of the quiet Sun (Elzner, 1976).

$\lambda$285.44 Å line having an intensity of 27.3 ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in the SERTS observation of an active region. From Table I, we find that Al VIII ion has other lines with observable intensities. We have shown the line emissivity ratios as a function of electron density for Al VIII at $T_{max} = 8.1 \times 10^5$ K in Figures 2 and 3. The dots in these figures correspond to the theoretical line intensity ratios, computed using the model atmosphere of Elzner (1976) for the quiet Sun. We find that the predicted ratios fall in the density-sensitive portion of the curves.

The electron density in the theoretical model at $8.1 \times 10^5$ K is $5.7 \times 10^8$ cm$^{-3}$. Thus the Al VIII lines should be sensitive to the electron density, as shown in Figure 2. We also see that the line ratios are sensitive to the density in the range $10^8$ cm$^{-3}$ to $10^{11}$ cm$^{-3}$. Therefore, these line ratios can, in principle, be used to

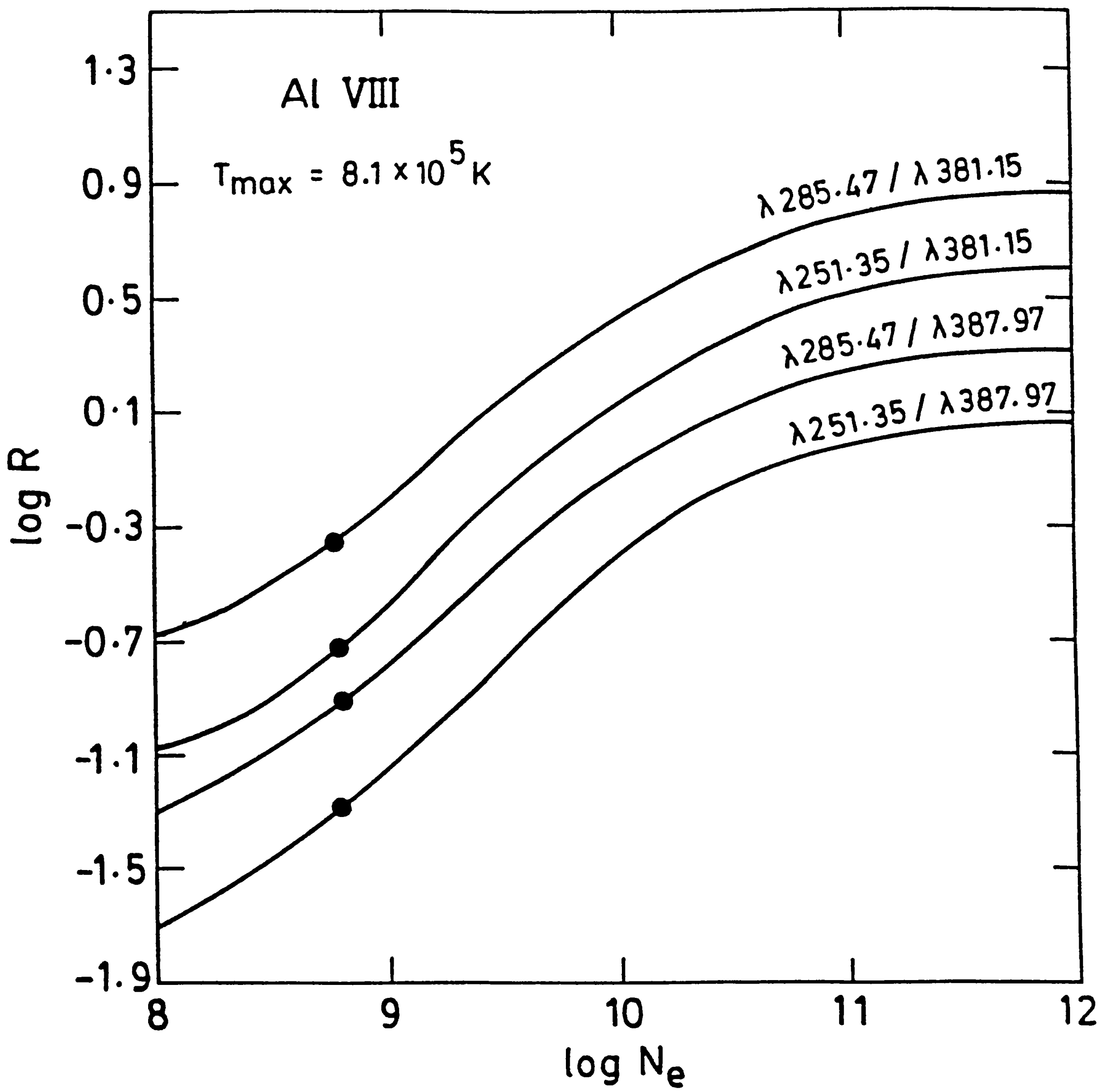


Fig. 3. Same as Figure 2.

determine density in different solar structures in chromosphere-corona transition region and the lower corona. This theoretical study will also be useful in resolving difficulties with line identification arising due to clustering and blending of other lines when observations from the CDS instrument on board the SOHO mission become available.

## 4. Conclusions

We have studied the density diagnostics of the less abundant Al VIII ion for solar plasma. Theoretical intensities computed using a model solar atmosphere give the impression, at first hand, that several Al VIII lines have observable intensities and should be observed by future solar missions. It is to be noted, however, that the strongest lines at 328.20 and 387.97 Å are, according to the SERTS line list, blended with lines of Cr XIII and Mg VI, respectively. The Coronal Diagnostic Spectrometer (CDS) instrument to be flown on board the SOHO mission will view these lines in bands N I (310–380 Å), G I (261–346 Å), and G I (198–248, 331–394 Å) in second order. But again, the spectral resolution of this instrument is no better than $\leq 0.12$ Å. Line ratio curves show density sensitivity over a wide range of densities and should, in principle, be useful to infer densities in different solar structures in the transition region and the lower corona. However, the EUV lines of Al VIII ion are weak and should be observed in active regions with longer exposures by an instrument at higher spectral resolution.

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